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Glasser, Neil F.; Sahlin, Eva A. U.

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A geomorphological map of Cadair Idris, Wales

EVA A.U. SAHLIN and NEIL F. GLASSER

Institute of Geography and Earth Sciences, Aberystwyth University, Llandinam Building, Penglais Campus. Aberystwyth, SY23 3DB, Wales, UK; eas04@aber.ac.uk

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Abstract: This paper presents a new 1:10 000 scale geomorphological map of Cadair Idris, Wales. The geomorphology was mapped by the interpretation of colour aerial photographs (scale 1:10 000) and field investigations of landform/sediment associations. Digital Elevation Models (horizontal resolution 5 m, vertical resolution 1 m) sourced from NEXTMap Britain were used to supplement the geomorphological mapping, significantly enhancing the ability to observe and identify landforms, bedrock structure and landscape composition. The geomorphological map shows the spatial distribution of glacial, periglacial and postglacial landforms such as cirques, end moraines, glacial striations, block fields, tors, meltwater channels, scree slopes and alluvial fans. Some of these features have not previously been identified, such as recessional moraines. The mapped landforms are used to make inferences about the glacial history of the area and will thereby give insight into the palaeoglaciology of the central Welsh uplands. The geomorphological mapping will also be used as basis for geoconservation planning by the Countryside Council for Wales and the Welsh Regionally Important Geological / Geomorphological Sites groups.

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1. Introduction

The reconstruction of the last British-Irish Ice Sheet (BIIS) by Bowen et al. (2002) describes the ice mass as a configuration of several independent ice domes. Reconstructions indicate that Wales was repeatedly covered by a terrestrially based Welsh Ice Cap (e.g. McCarroll and Ballantyne, 2000; Hambrey et al., 2001; Jansson and Glasser, 2005; 2008), in addition to the Irish Sea Glacier that encroached on the coast (e.g. Bowen, 1973; 1977; Thomas, 1985; 2005; Eyles and McCabe, 1989; Lambeck, 1995; Glasser et al., 2001; Etienne et al., 2006). The Welsh Ice Cap was semi-independent from the BIIS and had several dispersal centres in the upland areas of Wales (e.g. McCarroll and Ballantyne, 2000; Jansson and Glasser, 2005; 2008). However, there are no systematic landform inventory or mapping of the geomorphology of Wales, so the data these reconstructions are based on are fragmented and the reconstructions are poorly constrained (cf. Lambeck, 1995).

The aim of this study is to describe a detailed geomorphological map of Cadair Idris, an upland area in Wales (Figure 1) from aerial photograph interpretation. The map is part of a larger project titled "Developing a geomorphology map of Wales" which aims to provide a basis for detailed palaeoglaciological reconstructions of the Welsh Ice Cap, and to provide the Countryside Council for Wales (CCW) and the Regionally Important Geological/Geomorphological Sites groups (RIGS) groups with a basis for conservation recommendations of geomorphologic sites.

Mapping using aerial photographs and fieldwork are well-established tools for compiling the spatial distribution of landforms. Regional reconstructions of ice sheet configuration based primarily on mapping of geomorphology from aerial photographs and satellite images have been carried out in North America (e.g. Boulton and Clark, 1990; Jansson et al., 2002; Kleman et al., 2002; Stokes and Clark, 2003), Scandinavia (e.g. Borgström, 1989; Punkari, 1993; Kleman and Borgström, 1996; Kleman et al., 1997; Hättestrand and Stroven, 2002) and the British Isles (e.g. Clark and Meehan, 2001; Jansson and Glasser, 2005; 2008; Bradwell et al., 2008). Several attempts to account for the geomorphology of various parts of Britain have been made in recent years, mainly in relation to the development of geomorphological databases (e.g. Kirkbride et al., 2001; Clark et al., 2004). Examples of these geomorphological "portals" are the Geoconservation Review database of Britain, which describes over 3 000 geological and geomorphological sites

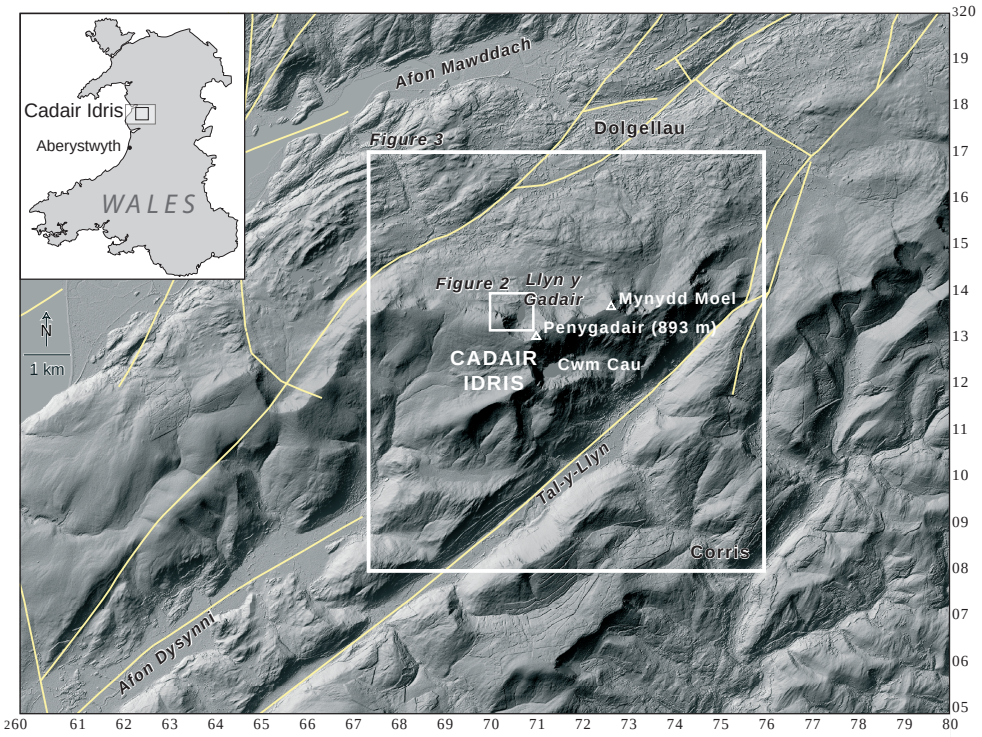

Figure 1. Digital Surface Model of the Cadair Idris area. Major faults are marked with yellow lines (cf. British Geological Survey, 1995). White box shows mapped area. NEXTMap Britain elevation data from Intermap Technologies in collaboration with the British Geological Survey (NERC). Coordinate System: British National Grid.

(Joint Nature Conservation Committee, 2008), and BRITICE by Clark et al. (2004), a 1:625 000 scale glacial map and GIS database of landforms related to the last British Ice Sheet.

Landforms which can be mapped from aerial photographs and which are of interest for palaeoglaciological reconstructions (e.g. indicating basal thermal regime, flow direction and extent of glaciation) include: cirques, ice-moulded bedrock, moraines, glaciofluvial deposits, glacial meltwater channels, trimlines and tors, but also the amount of glacial imprint the landscape exhibits as a whole. A comprehensive table of the glaciological significance of these landforms is described in detail by Hubbard and Glasser (2005, p291-293). The geomorphological map of Cadair Idris shows all identifiable types of glacial and deglacial (both erosional and depositional) landforms, as well as other relevant topographical and geomorphological features.

1.1 Geographical setting

Cadair Idris [52°42'N; 03°54'W; SH 7113] is situated 5 km south of Dolgellau in the southern part of the Snowdonia National Park (Figure 1). The area is dominated by the mountain massif of Cadair Idris consisting of a west-east trending high plateau ridge ca. 650-890 m O.D., defined by an 8 km long and up to 250 m high north-facing escarpment. The highest summits are Penygadair (893 m O.D.) and Mynydd Moel (863 m O.D.). Cadair Idris contains some of the finest assemblages of glacial erosional features that can be found in Wales. Several glacial cirques are cut into the escarpment and the plateau, including Cwm Cau which is renowned for being one of the finest cirques in Britain (Campbell and Bowen, 1989). A rich contribution to the geomorphological knowledge of Cadair Idris was made by Watson (1960; 1962; 1977). Cadair Idris is a key site, although controversial, for reconstructing the dimensions of the ice sheet at the Last Glacial Maximum (LGM) in the Late Devensian and during the Younger Dryas (Ballantyne, 2001; Lowe and Lowe, 1989). The survival of summit plateau tors and extensive blockfields can both be explained by nunatak formation or preservation under cold-based ice (Ballantyne, 2001; Jansson and Glasser, 2005).

1.2 Glacial history

The Pleistocene Epoch in general was characterised by a climate much cooler than the present interglacial (e.g. Ehlers and Gibbard, 2007). It is feasible that cirque and small valley glaciations during this time dominated the higher ground in this part of Wales (McCarroll, 2005). Thus repeated small-scale glaciations, rather than large ice sheets, were the main landform-creating agents during the Pleistocene (cf. Porter, 1989; Kleman and Stroeven, 1997).

During the Late Devensian the main ice movement was across the Cadair Idris area from the north-east to the south-west (Foster, 1968; Pratt et al., 1995), fed from the interior of the Welsh Ice Cap. The ice discharged through the major valleys of Mawddach, Tal-y-llyn, and Dysynni, exploiting and over-deepening pre-existing valleys developed along lines of structural weaknesses (cf. Cave and Hains, 1989; British Geological Survey, 1995; Pratt et al., 1995). This ice joined the Irish Sea Glacier, which flowed

south through the Irish Sea from Scotland and the Lake District (Foster, 1970; Garrard and Dobson, 1974; Garrard, 1977; Allen and Jackson, 1985; Eyles and McCabe, 1989; Hambrey et al., 2001).

Whether the higher parts of Cadair Idris remained ice-free during the LGM, or were submerged by the ice sheet, is unresolved. Ballantyne (2001) proposed that Cadair Idris was a nunatak during the LGM, citing the existence of tors and frost-weathered debris (in situ blockfields) on the plateau as evidence for this. Gibbsite, a weathering end-product of silicate minerals often found in remnant soils on former nunataks (McCarroll and Ballantyne, 2000), is present in the summit blockfields but is absent in the glacially modified landscape below. The palaeonunatak model proposes that the ice sheet over Wales was not thick enough to bury all the mountains, which survived as nunataks. However, another possibility is that the summits were covered by cold-based ice, which effectively protected the landscape from erosion, preserving the tors, blockfields and gibbsite (Ballantyne, 2001). Ice sheet models developed by Jansson and Glasser (2005) support this view. Foster (1968, p245) described poorly preserved grooves near the summit of Penygadair with orientation 220°, indicating ice passing over Penygadair towards southwest. However, it has not been possible to reconfirm these from field visits.

No record of pre-Devensian glaciations in the form of landforms or sediments has been found in the Cadair Idris area. Most landforms are presumed to be Late Devensian in age, modified by periglacial activity. During the Younger Dryas, glaciers reformed in many of the mountain cirques of Cadair Idris (Lowe, 1993; McCarroll, 2005; Pratt et al., 1995), as well as other parts of the Welsh uplands (e.g. Gray, 1982; Addison et al., 1990; Gray and Coxon, 1991; Walker and McCarroll, 2001; Hughes, 2002; Carr et al., 2007). The end moraines and protalus ramparts found around Cadair Idris are inferred to date from this brief glaciation (Lowe, 1993).

2. Methods

The Cadair Idris map shows the geographical distribution, morphology (appearance, shape), morphometry (size), morphogenesis (origin) and soil cover (substrate) of the geomorphological features where possible. The choice of colours and symbols for the map primarily follows the guidelines

of international conventions (Demek et al., 1972). Adaptations have been made to the map layout in order to make it readable by non-specialists.

The map covers an area of 8.5 x 9 km [UK Ordnance Survey grid reference SH 675080 - 760170]. The interpretation and mapping are based on 66 hard copy vertical colour aerial photographs from 1992, scale 1:10 000 (Countryside Council for Wales). Interpretation was made with a Hilger and Watts mirror stereoscope with 2x - 6x magnifications, and a WILD Aviopret with 3x -15.5x magnification. Stereo pairs of aerial photographs were viewed and interpreted at least twice for accuracy and the geomorphological elements were drawn on acetates. The interpretations were cross-checked with the Coflein online database from the National Monuments Record of Wales (National Monuments Record of Wales, 2008), in order to avoid misinterpretation with man-made features (for example 17^{th} Century mining spoil heaps can be easily confused with hummocky moraine when overgrown). As the aerial extent of an aerial photograph stereo pair at 1:10 000 scale is less than 1 km^2, the context with the surrounding landscape is easily lost when interpreting a large number of photographs. To remove this effect, a Digital Elevation Model (DEM), sourced from NEXTMap Britain, was used for overviews (Figure 1). The DEM was also used to identify and separate problematic cases of differential glacial erosion, for example by analysing cross-valley profiles.

Geometric distortion in aerial photographs due to a constant flying height in relation to changing topographic relief, causes both vertical and horizontal displacement which needs to be rectified (Lillesand et al., 2004). The height interval in the mapped area of Cadair Idris ranges from 40-893 m O.D. It is difficult to obtain good results from digital rectification of steep mountain areas, as they generally lack adequate fixed points in the form of roads, buildings and hydrology. This is especially a problem when working at detailed scales such as 1:10 000, as the errors visually stand out so much more compared to higher scales. Rectification was therefore achieved manually using a light table, on which the acetates were placed between a topographic base map (scale of 1:10 000) and a tracing sheet. The geomorphological data were then drawn on the tracing sheet, and where necessary the acetates were moved for a best-fit in relation to topographic features (contours, hydrology, etc.), to produce a best-approximation georeferenced manuscript map. The manuscript map (12 tracing sheets in A3) was scanned and exported as a background picture (tiff) into a software package (Adobe Illustrator 10) and aligned with the Ordnance Survey national grid. The scanned artwork was then

digitized. The estimated accuracy of landform position on the resulting map is < 20 m in the horizontal dimension. Contour lines were created from the NEXTMap Britain DEM and compiled in ArcGIS 9.0. Other map data, such as roads and hydrology, were derived from various sources, such as aerial photography, DEMs and topographic maps. True north is indicated with a North arrow, drawn from the 1:25 000 Ordnance Survey Explorer Series map (sheet OL23, 2002).

Aerial photograph interpretations were validated with fieldwork over 14 days from 2004-2008. Additions and corrections to the map were made where necessary. Glacial erosional features indicating directions of glacier flow, such as glacial striations, grooves, roches moutonnées and ice-moulded bedrock ridges were mapped and measured in the field with a SILVA 360° compass with clinometer. A Garmin eTrex GPS was used for site positioning of glacial striations.

The geomorphological map of Cadair Idris is presented in its original size of 1060 x 960 mm, and is best printed in B0 format (1064 x 962 mm).

3. Results and Conclusions

This is the first time the investigated area has been geomorphologically mapped in detail at this scale. The geomorphological map shows the spatial distribution of glacial, periglacial and postglacial landforms, and the rich geomorphological geodiversity of Cadair Idris. Comparison with previous geomorphological studies and the mapping presented here, shows differences in interpretation. For example, Lowe (1993) interpreted the western lobe of ridges and boulder-strewn terrain west of Llyn y Gadair as the remnants of an ice-cored rock glacier. However, seven ridges can be identified over a length of 300 m; the three outermost are clearly separated from each other, while the inner ridges are more of a composite nature, merging with moraine hummocks and ridges (Figure 2). The western lobe is interpreted here to represent a set of recessional moraines, formed by a debris-covered glacier originating from the headwall of Cyfrwy, as evidenced from glacial striations. The composite ridges indicate glacier readvance occurred during deglaciation (cf. Ballantyne, 2001). It is, however, possible that during recession the glacier became more of an ice-cored rock glacier, as there is indication of "ridge-and-furrow" flow structures within the rock masses (cf.

Barsch, 1996) which lies below the headwall of Cyfrwy.

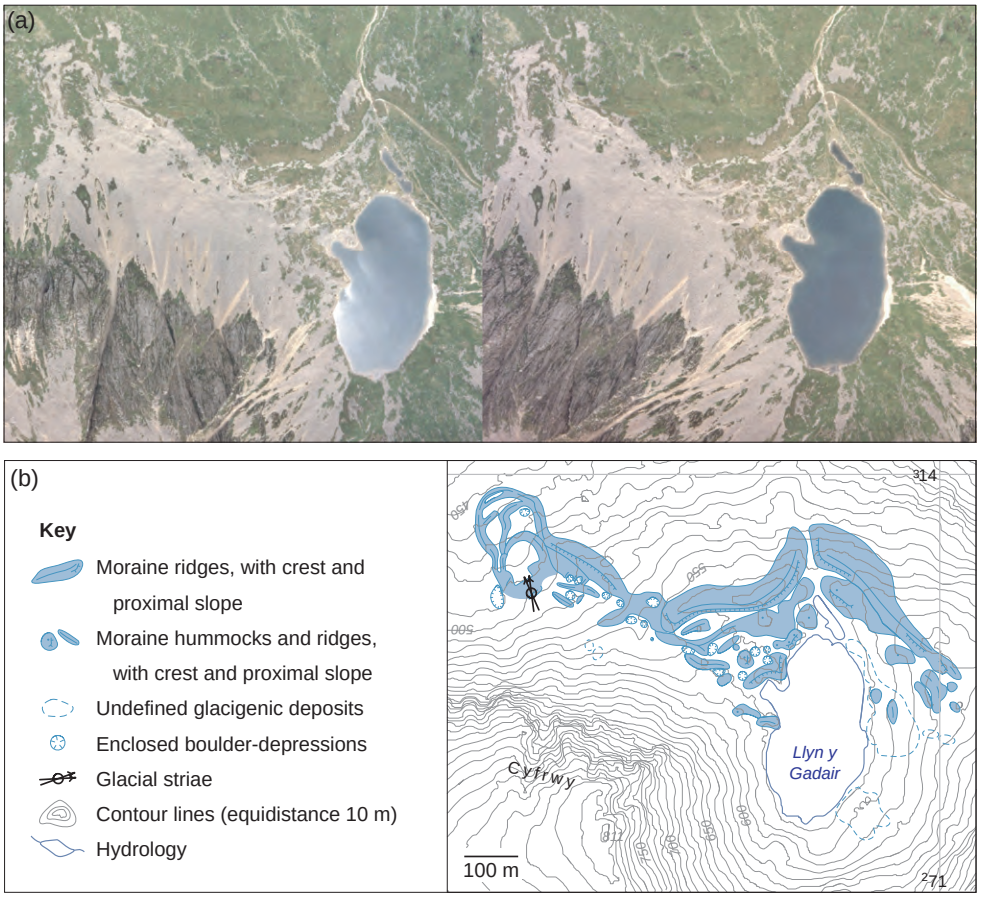

Figure 2. (a) Stereogram and (b) interpretation of the glacial depositional landforms in Cwm y Gadair. Aerial photographs ©Cyngor Cefn Gwlad Cymry, 1992. ©Countryside Council for Wales, 1992. NEXTMap Britain elevation data from Intermap Technologies in collaboration with the British Geological Survey (NERC). Coordinate System: British National Grid.

The Cadair Idris area can be divided into four main domains based on the degree of glacial imprint (Figure 3). The mapping supports previous work that the ice-flow direction was across the areas from the northeast during the LGM. Interpretation based on aerial photographs and DEMs indicate that the massif acted as an obstacle, dividing ice flow into Tal-y-llyn and to the area north of Cadair Idris, resulting in heavy scouring and over-deepening along zones of bedrock weakness. The summit plateau of Cadair Idris experienced little or no glacial erosion, but rather severe periglacial conditions, as seen by the blockfields and tors. It is not clear if the survival of these landforms is due to a cold-based ice carapace preserving the surface or if it is due to nunatak conditions, or if the summit

surfaces were glaciated and later extensively modified by periglacial action. Cosmogenic radionuclide dating may shed some light on this. On the western "lee-side" of the massif, the abundance of blocks in the drift suggests a source from former blockfields on the western slopes of Cadair Idris, which might indicate that ice covered the summits at least once.

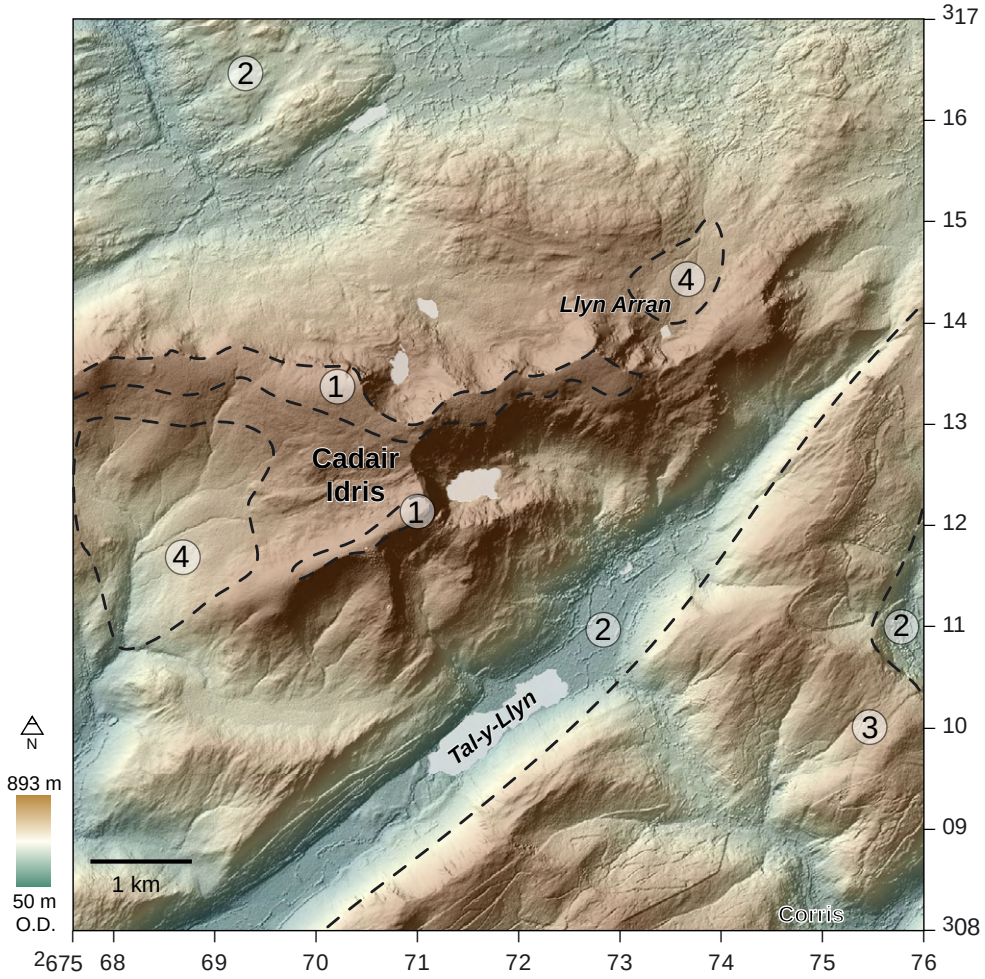

Figure 3. Relief-shaded Digital Elevation Model of Cadair Idris. Numbers indicate main areas of glacial erosion: (1) little glacial erosion on the smoothly undulating summit plateau with tors and covered by frost-shattered detritus, (2) heavy glacial erosion in the form of steep cirques and headwalls surrounding the summit plateau, and flanking the massif; the ice-scoured hills north of Cadair Idris and the glacially over-deepened valley of Tal-y-Llyn to the south, (3) less prominent glacial imprint and little drift cover in the south uplands around Corris, and (4) extensive glacial deposition in the river valley to the west of Cadair Idris and north of Llyn Arran. NEXTMap Britain elevation data from Intermap Technologies in collaboration with the British Geological Survey (NERC). Coordinate System: British National Grid.

For detailed geomorphological mapping, the use of the DEMs from NEXTMap Britain is an advantageous complement in landscape analysis,

such as identification of palaeo-drainage pattern, glacial impact and bedrock structure. However, detailed aerial photographs and subsequent fieldwork are the only means of identifying more delicate landforms, such as small moraines, patterned ground, tors and small-scale glacial erosional features such as glacial striations.

Software

The Cadair Idris map is drawn in Adobe Illustrator 10. The NEXTMap Britain DEM was used for the geomorphological mapping of Cadair Idris with data manipulation performed in ArcGIS 9.2.

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